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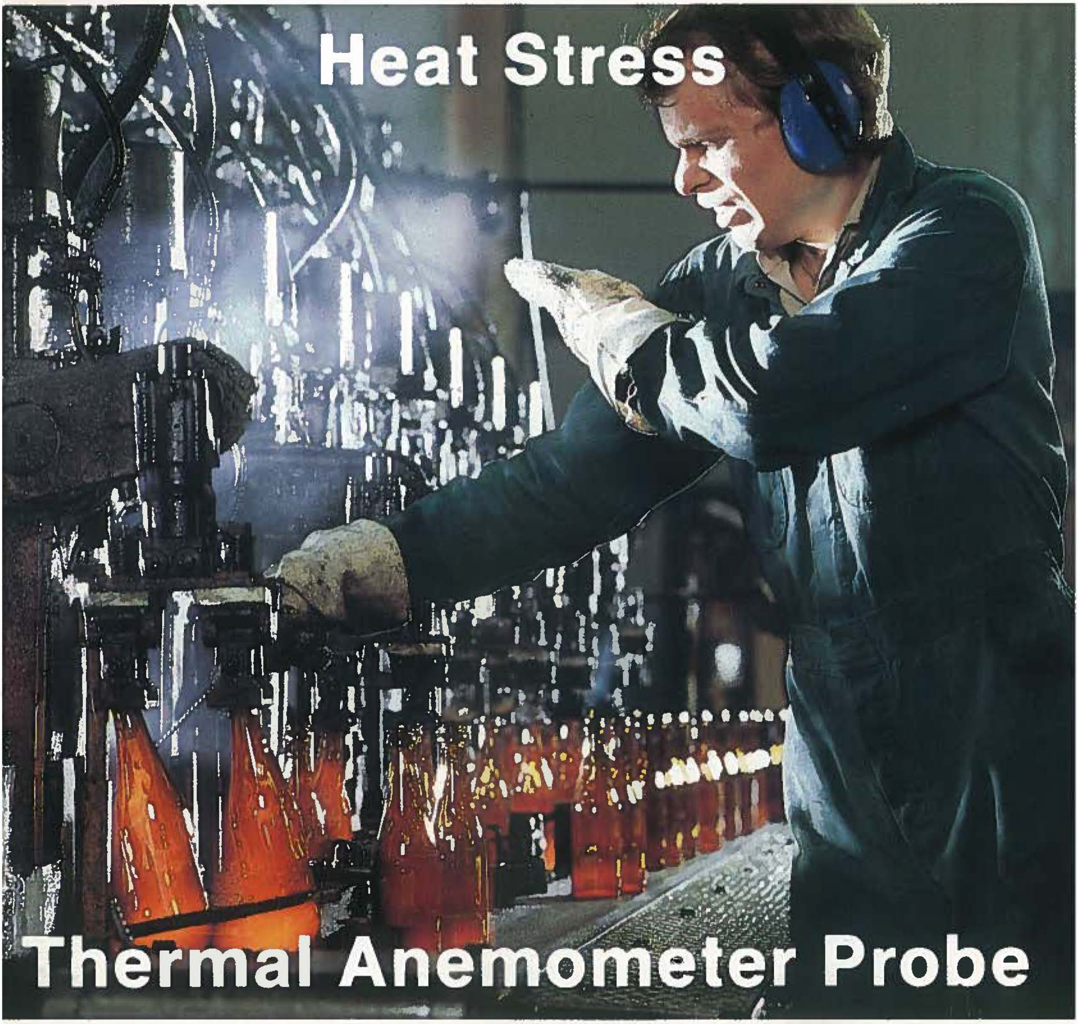

Heat Stress

Thermal Anemometer Probe

Brüel & Kjær

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TECHNICAL REVIEW

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HEAT STRESS

by

Bjarne W. Olesen, (Ph.D.)

ABSTRACT

Heat stress is a major problem in several working environments. Although technology has brought about remote control of industrial processes from air-conditioned cabins, there are still many people who have to work in hot environments. Several methods for evaluation of heat stress have been presented in the literature.

This article describes the method of evaluation of heat stress by means of the WBGT-index, which has been standardized recently in the International Standard ISO 7243. Physiological reactions in hot environments are shortly described. Through the years several heat stress indices (both empirical and analytical) have been developed and used. The most common are also presented here.

SOMMAIRE

La contrainte thermique est un problème important sur de nombreux postes de travail. Bien que grâce aux progrès technologiques on puisse utiliser la commande à distance des procédés industriels à partir de cabines à air conditionné, il y a toujours beaucoup de gens qui doivent travailler dans des environnements très chauds. On trouve dans la littérature plusieurs méthodes d'évaluation de la contrainte thermique.

Cet article décrit la méthode d'évaluation de la contrainte thermique fondée sur l'indice WBGT qui a été standardisé récemment dans la Norme internationale ISO 7243. Les réactions physiologiques aux environnements très chauds sont décrites brièvement. Au cours des années passées, plusieurs indices de contrainte thermique (empiriques comme analytiques) ont été élaborés et utilisés. Les plus courants sont passés en revue ici.

ZUSAMMENFASSUNG

An verschiedenen Arbeitsplätzen spielt Hitzestreß eine wesentliche Rolle. Zwar ermöglichen neue Technologien in zunehmenden Maße industrielle Prozesse von klimatisierten Kabinen aus fernzusteuern — viele Tätigkeiten müssen jedoch unter extremen thermischen Bedingungen durchgeführt werden. In der Literatur werden verschiedene Methoden zur Beurteilung von Hitzestreß behandelt.

Dieser Artikel beschreibt, wie Hitzestreß anhand des WBGT-Index beurteilt werden kann. Diese Methode wurde kürzlich in ISO 7243 international festgelegt. Die physiologischen Reaktionen unter extremer Hitzeeinwirkung werden kurz beschrieben. Die gebräuchlichsten der in den letzten Jahren ausgearbeiteten und benutzten Hitzestreß-Indizes (sowohl empirische als auch analytische) werden vorgestellt.

Introduction

For several years **"heat stress"** has been a common subject in literature dealing with the thermal environment. There are many books, technical papers and recommendations that deal with the problem of heat stress, how the human body reacts to it, how it should be evaluated and what limitations apply, [1,2,3,4].

Heat stress may occur in environments with high air temperatures (summer–time), high thermal radiation (foundries, steel mills, glass and ceramic factories, brick factories, cement plants, coke ovens etc.) high levels of humidity (mines, laundries) or at workplaces where a high activity level (increasing metabolic rate) or protective clothing are needed. Also outdoor work like construction, agriculture, sport activities and others in hot climates may result in heat stress.

Whenever heat stress from the thermal environment is imposed on the human body, there will be a resulting strain in the body. This may result in physiological reactions such as increased skin temperature, sweat production, increased heart rate and higher core temperature. Under severe conditions the strain may attain such a magnitude as to cause health impairment.

The purpose of this present article is to give a short description of the physiological reactions and health risks, that may occur by working in hot environments.

The heat stress imposed on the human body by a certain environment is often evaluated by a "heat stress index", which by a single value combines the influence of one or more of the environmental factors as air temperature, mean radiant temperature, air velocity, humidity, activity and clothing. Several heat stress indices have been proposed in literature. In this article the most common indices will be described shortly.

Finally a detailed presentation of the *WBGT*-index (Wet Bulb Globe Temperature) and how it is used is given. This heat stress index is the most widely used and has been internationally standardized in ISO 7243 (5).

Physiological reactions in hot environments

Man's thermoregulation

As in moderate thermal environments the thermoregulatory system of the human body tries to keep a heat balance, i.e. the heat produced by the activity should be equal to the amount of heat gain/loss due to convection, radiation and evaporation. The heat balance equation is written as:

$$S = M - W - R - C - E - C_{res} - E_{res} - K$$

where S = heat storage rate W/m^2
M = metabolic rate W/m^2
W = external work W/m^2
R = heat loss by radiation W/m^2
C = heat loss by convection W/m^2
E = heat loss by evaporation W/m^2
C_{res} = dry heat loss by respiration W/m^2
E_{res} = latent heat loss by respiration W/m^2
K = heat loss by conduction W/m^2

Heat is lost by conduction (K) from parts of the body which are in contact with surrounding surfaces or tools (hands, feet). This heat loss has no significant influence on total heat exchange of the body as a whole and is therefore generally neglected in the heat balance equation. It may, however, have a significant influence on local heat discomfort or cause burns. The heat exchanges by respiration (C_{res}, E_{res}) are also negligible in hot environments and the external work (W) may in most situations also be set to zero, to be on the safe side.

If the heat content of the body has to remain constant, i.e. heat storage (S) is equal to zero, then the combined heat loss by convection (C), radiation (R) and evaporation must be equal to the metabolic heat production ($M - W$). In hot environments it is often a question of heat gain by radiation and possibly also convection, because the mean radiant temperature and also the air temperature are often higher than the body temperature.

The environmental heat load may then be caused by a situation, where the evaporative heat loss is not sufficient to compensate for the heat gain from radiation and from convection. The heat load on the body may also be caused by a high metabolic heat production. Activity or muscle work results in an energy production. Because the mechanical work efficiency of the human body (W/M) can vary between 0 and 25% depending on the type of work at least 75% of the energy is transformed to heat. Well-trained atheletes may during 5–10 min intensive activity reach a heat production around 2000 W (6) and during a longer activity around 1500 W. Theoretically the produced heat during one work period at this level may increase the body temperature of a 70 kg person from 37°C to 60°C if no heat is exchanged with the environment.

The aim of the temperature regulation is to control the body temperature and then the heat balance. The regulation tries to keep the temperature constant at ~37°C in certain organs like the brain, the heart and intestinal canal. The centre for the temperature regulation is in the hypothalamus in the brain. Its function is similar to a thermostat and its set point can be changed by different physiological conditions. Temperature sensors located mainly in the skin influence the set point of the thermostat.

When a person is exposed to hot environments or is engaged in increased activity the blood vessels will dilate (vasodilation). The blood flow will increase in the peripheral blood vessels and the heat will be conducted from the body core to the skin. This will facilitate the transport of metabolic heat to the skin surface. Skin temperature will increase especially on the extremities (arms, hands, legs, feet). If the environmental temperatures (air temperature, mean radiant temperature) are lower than skin temperature the heat loss due to radiation and convection will increase or else the heat gain by convection and/or radiation will decrease. If the heat load is high enough the sweat glands will be activated and the evaporation of sweat will cool the skin. 1 g of water (sweat) which evaporates removes 2,47 kJ. A person may have about 2000 sweat glands in the skin, but the activation of sweat glands on different skin areas is not the same for different individuals. The individual variation is great. Some individuals have no sweat glands at all. When a human body starts sweating, sweat is not produced evenly over the whole skin surface. Sweating starts locally and then spreads gradually over a greater surface area. At a certain stage, often before the whole surface is covered with sweat, some sweat will drip off. This sweat does not help to cool the body, because it does not evaporate at the skin surface. Instead it increases the strain on the body system. The increased skin temperature and sweating will result in an increase of the heart rate.

When the evaporation of sweat is not enough to keep the body in heat balance, the internal body temperature increases. A new heat balance may be established at a higher body temperature or the internal temperature may increase even further in an uncontrolled manner that may result in heat casualties and eventually even death.

The strain in the body can thus be expressed in terms of increase in skin temperature, deep body temperature, heart rate and sweat loss. There are of course limitations to the level of strain which the body can tolerate. Most of these limitations are shown in Table 1, which are the values suggested in an International Draft Standard, ISO/DIS 7933(7). The limits are shown for two levels of strain: Warning and danger. On the warning level the work may proceed provided extra precautions are taken, because some persons may have problems. On the danger level the work should be stopped and a new work/rest routine should be established. Besides the limits are dependent on whether or not the person is acclimatized (see later).

From the table it is seen that a person can sweat more when he is active than when he is resting. The skin wettedness is the skin surface area which is covered with sweat as percentage of the total body surface area. The pain threshold for the skin temperature is approximately 45°C.

Acclimatization to heat
Heat acclimatization is the physiological adjustments that can occur when a person not accustomed to hot environments is exposed to heat for a period of time. After a few days exposure to a hot environment a person is more capable of tolerating the conditions than at the beginning

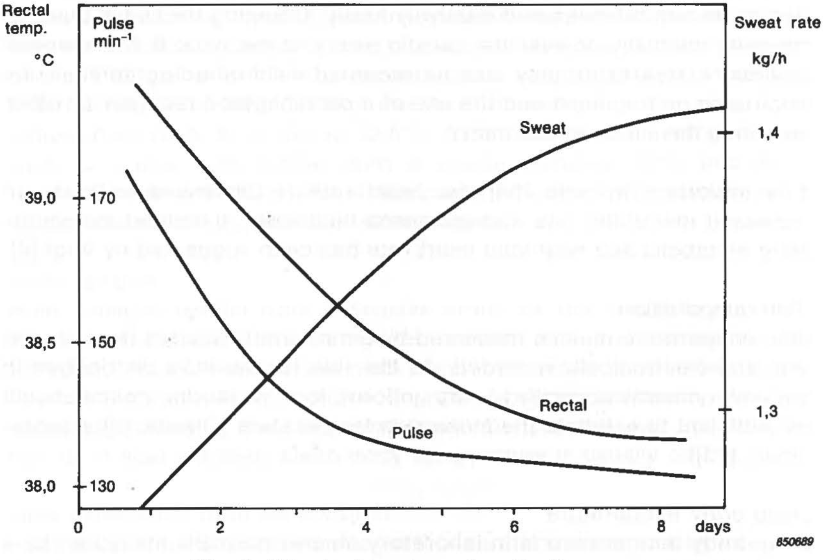

Fig. 1. Effect of heat acclimatization

of the period. This improvement in heat tolerance is due to an increased ability of sweating, a lowered skin- and body temperature and a lower heart rate, (Fig.1). In addition, sweating starts already at a lower core and skin temperature and the content of salt in the sweat is reduced. Most of the changes take place during 4–7 days of exposure to heat and after 12–14 days the acclimatization is complete. A person in good condition and well-trained can better tolerate heat than a person in bad condition, but training cannot substitute acclimatization completely.

The effect of acclimatization may last several weeks after a period of exposure to heat. A certain decrease in heat tolerance can be seen after a couple of days after the heat exposure. This may happen after a long weekend, so it is always recommended not to work under most severe conditions on a monday. This is especially important if the person is tired and has consumed alcohol.

Assessment of heat strain by physiological measurements

By measuring physiological parameters as heat rate, skin temperature, deep body temperature and sweat loss it is possible to evaluate the heat stress and the strain it imposes on the body. This way of measuring may also take individual differences into account.

Heart rate

Heart rate can be measured relatively easily. Counting the radial pulse at the wrist manually or over the carotid artery at the neck is the simplest procedure. Heart rate may also be recorded electrocardiographically by electrodes on the chest and the use of a portable tape recorder or other recording device or by telemetry.

It is important to note that the heart rate is influenced both by an increased metabolic rate and increased heat load. A method for separating metabolic and heat load heart rate has been suggested by Vogt [8].

Skin temperature

Skin temperature may be measured by temperature sensors taped to the skin and electronically recorded. As the skin temperature distribution in hot environments normally is very uniform, four measuring points should be sufficient to estimate the mean skin temperature (Olesen, [9], Ramanathan, [10]).

Deep body temperature

Deep body temperature is in laboratory studies normally measured by a rectal temperature probe or by an esophageal probe. These methods are, however, not very feasible to use in the field. Also the measurement of ear- (tympanic) and armpit temperature may be difficult to perform. The most widely used method, which is found acceptable by most industrial workers is the measurement of oral temperature.

Precautions such as temperature probe under tongue for five minutes, breathing through the nose, no drinking or eating prior to measurement are necessary to get a representative measurement. The deep body temperature may then be estimated from the oral temperature by adding 0,4°C to it.

Sweating and dehydration
Sweating and dehydration can be measured by monitoring the body weight loss and making corrections for fluid intake and output.

Heat disorders

Heat disorders may be due to heat stroke, heat collapse, heat exhaustion (dehydration, salt depletion), heat cramps and diseases of sweat glands.

Heat stroke
Heat stroke may occur when the thermoregulatory system cannot cope with the heat stress level and the deep body temperature rises continually, brain function is impaired and the mechanisms for dissipation of heat may not function. Symptoms are collapse, convulsions, delirium hallucinations and coma which sometimes occur without previous warning. External signs of heat stroke are hot, flushed and dry skin. Core temperature rises to or above 40,5°C. When the persons suffer convulsions or coma, core temperature is usually between 42°C and 45°C. Heat stroke is very often fatal and in cases of survival there is frequently damage to the brain, kidney or other organs.

Heat collapse
Heat collapse results from excessive strain on the circulatory system. The symptoms are dizziness, pallor, sweaty skin and headache. The increased blood flow at the skin level and working muscles in hot environments may lead to some degree of oxygen deficiency. This will especially influence the brain and heart. Dehydration will increase the risk for a heat collapse. Deep body temperature is usually normal.

Heat exhaustion from dehydration
Heat exhaustion from dehydration will occur if the water lost by sweating is not replaced through the intake of liquids, the water content of the

body will decrease. Usually workers engaged in hot jobs drink less during the workday and go home somewhat dehydrated. However, they usually replace their fluid deficit during the rest of the day, so that next morning they return to work with a restored fluid content in their bodies. If the dehydration does not exceed 1,5% of their total body weight during the day, this drinking pattern is harmless. A fluid loss in excess of 1,5% of the body weight will result in decrease of heat tolerance as exhibited in higher heart rates and body temperatures. Unfortunately, man does not have the ability to recognize a slight dehydration in his body nor can he notice the loss of fitness. Particularly in dry climates, as for instance, in the desert, where the sweat is immediately evaporated from the skin, man may not even be aware of the fact that he is sweating heavily. Under these conditions, dehydration may reach a level where not only physical fitness and heat tolerance are decreased but mental capacity as well, causing misjudgement of dangers, erroneous decisions, loss of skill and increased reaction time. In such a state worker may be prone to accidents and may be more susceptible to some intoxications.

Heat exhaustion due to salt depletion

Heat exhaustion due to salt depletion occurs if salt intake is inadequate to replace losses of sodium chloride caused by sweating. It is mostly seen in inacclimatized men who drink a lot of water without giving thoughts to salt replacement.

Heat cramps

Heat cramps are sharp pains in muscles in which there has been a great physical activity. Heat cramp occurs in unacclimatized workers who are sweating heavily and are at the same time drinking large amounts of unsalted water.

Dehydration, heat cramps and salt depletion may be prevented by drinking water and other fluids regularly during work. Thurst is, however, not a good indicator of the amount of fluid which is necessary. Normally a person must drink much more to avoid dehydration. Additional salt intake is normally not necessary since the daily salt intake through food will in most cases exceed the salt loss by sweating.

Diseases of the sweat glands

Diseases of the sweat glands may occur after prolonged exposure (months) to heat in an environment, where sweat cannot evaporate freely (humid environment). Sweat glands over certain areas of the skin may stop producing sweat. This will decrease sweating and the person will then become less tolerant to heat. This is often connected with a skin rash called prickly heat.

It is very important to be aware of the great individual differences in the tolerance to heat. Also factors such as age, sex, ethnic characteristics, body build, nutrition, general health conditions, habits like smoking and alcohol, acclimatization etc. are significant for man's response to heat.

Heat stress indices

The most efficient and accurate method of evaluating whether an environment is too hot and risky is to take direct measurements of internal body temperature, pulse rate and possibly sweat rate of the exposed individuals and compare these with the recommended guidelines in Table 1. This is of course very difficult and in most cases is not acceptable to those involved. Consequently, there has long been an interest in determining a combination of the environmental parameters (air temperature, mean radiant temperature, air velocity, humidity), activity level and clothing level, which can express the level of heat stress, i.e. be related to the physiological reactions of the human body.

			Not-acclimatized		**Acclimatized**	
			Warning	**Danger**	**Warning**	**Danger**
Maximum Sweat-rate	Resting	W/m^2 (g/h)	100 (260)	150 (390)	200 (520)	300 (780)
	SW_{max} Arbejde	W/m^2 (g/h)	200 (520)	250 (650)	300 (780)	400 (1040)
Skin humidity	W_{max}		0,85		1,00	
Dehydration	D_{max}	Wh/m^2 (g)	1000 (2600)	1250 (3250)	1500 (3900)	2000 (5200)
Heat Storage	Q_{max}	Wh/m^2	50	60	50	60
Corresponding change of Rectal– and Skin temperature	Δt_{re}	°C	0,8	1	0,8	1
	Δt_{sk}	°C	2,4	3	2,4	3

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Estimation of sweat in g/h or g are based on a mean person with 1,8 m^2 surface area

Table 1. Recommended physiological limitations

Between 30 and 40 different suggestions for a heat stress index exist in the literature. Every scientist, who has studied these problems, has more or less established his or her own heat stress index.

The aim of a heat stress index is to combine the environmental variables into a single value, which quantitatively describes the stress that a thermal environment places on an individual. Stress is something which when applied to a system produces a strain. The simple mechanical analogy is the strain in a spring produced by a force (stress).

Comfort indices aim to predict either thermal sensation or subjective discomfort. However, in hot environments where there is danger of heat disorder, sensation is an inadequate guide to physiological strain and it is necessary to employ an index which has been developed specifically for the task.

The most elementary requirement of an index is that different environmental conditions that produce the same strain in a person, should all have the same value of a heat stress index. For instance, two environments A and B, one with a high air temperature and low humidity, and the other having a low air temperature and high humidity, which both produce the same strain in a person, should have the same value of a heat stress index.

Heat stress indices can be divided into either analytical or empirical heat stress indices.

Analytical heat stress index
An analytical heat stress index is normally based on analysis of the human heat balance and heat exchange with the environment. This kind of index always includes the four environmental factors and normally also activity and clothing levels.

Empirical heat stress index
An empirical heat stress index is normally based on a correlation between two or more of the thermal parameters and a human response. This relation is estimated from tests with human beings.

While an analytical index may be used generally, an empirical index is often limited to those environments on which it has been based. Through experience and further research an empirical index may be shown to be valid for a broader range of environments. The most common and widely accepted heat stress indices are described below.

Empirical heat stress indices

The "Effective Temperature" Index (ET)

The Effective Temperature index was developed between 1923 and 1925 at the research laboratory of the American Society of Heating and Air Conditioning Engineers, by Houghten, Yaglou and Miller [11]. This index takes account of air temperature, humidity and air velocity.

The criterion for determining the effects of these parameters was the instantaneous thermal sensation experienced by the subjects upon entering a given environment. The unit, or basis, of the ET-index is the temperature of saturated "still" air with an average velocity of 0,12 m/s. Any combination of air temperature, humidity and air velocity having a given value of ET is supposed to produce the same thermal sensation; this is equal to that experienced in saturated still air at the same temperature as the value of the index.

In the experiments from which this index was developed, subjects walked to and fro between two rooms with different combinations of the environmental parameters mentioned. The conditions in one room were adjusted so that the subjects felt the same thermal sensation when passing from one room to the other.

The Effective Temperature index is in the form of two nomograms from which its value can be determined for any combination of dry and wet bulb temperatures and air velocity (Fig.2 and Fig.3). One nomogram is for semi-nude men and one for people clad in lightweight clothing.

Corrected Effective Temperature (CET)

Because the ET-index does not consider thermal radiation effects, a correction has been suggested when radiant heat contributes to the heat load. The temperature as measured by a black globe thermometer is then used to calculate CET, using the ET charts, instead of the dry bulb temperature (Fig.2).

Predicted Four Hours Sweat Rate (P4SR)

The P4SR index was developed during World War II at the Royal Naval Research Establishment in England by McArdle and colleagues [12]. The P4SR is a heat stress index based on the concept that the sweat rate is an adequate index of the heat stress. Its value is nominally the amount of sweat secreted by fit, acclimatized young men exposed to the environment for four hours. The stress of the environment is therefore measured by the strain it produces. This is reasonable provided that the behaviour of the stressed system is reproducible. This was ensured in the original

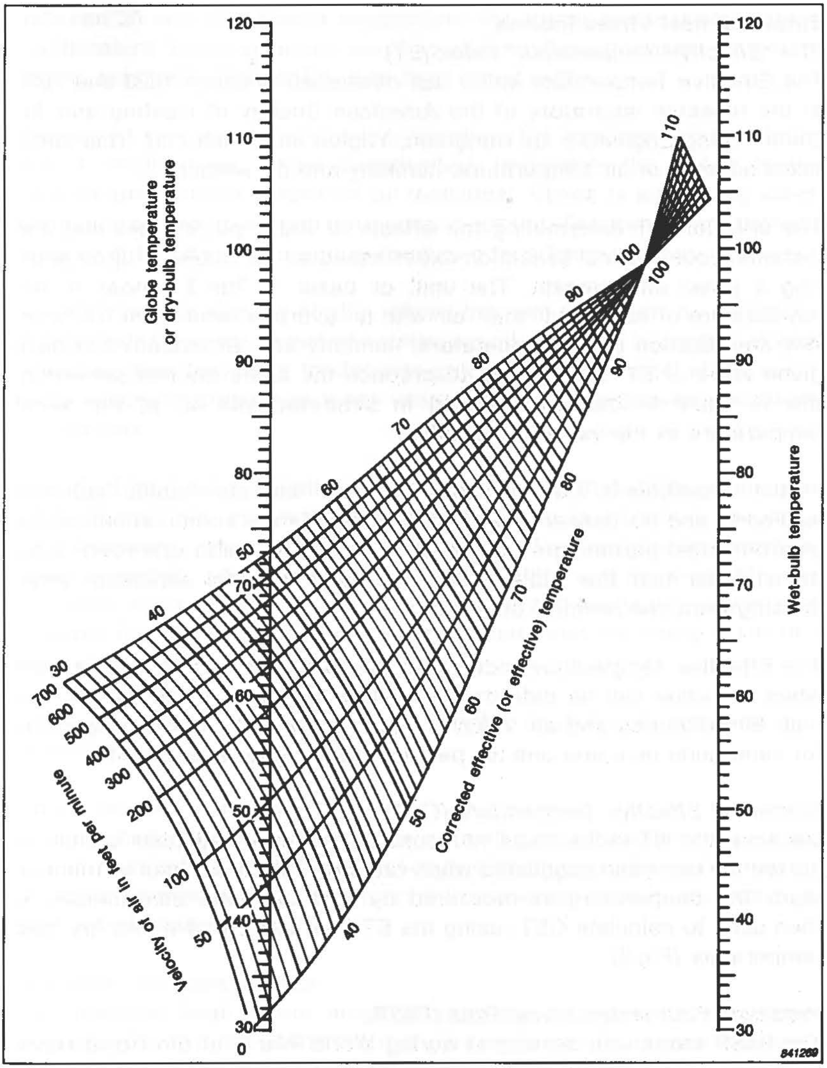

Fig. 2. The “basic” Effective Temperature scale, i.e., for men stripped waist. This scale is also used for Corrected Effective Temperature index

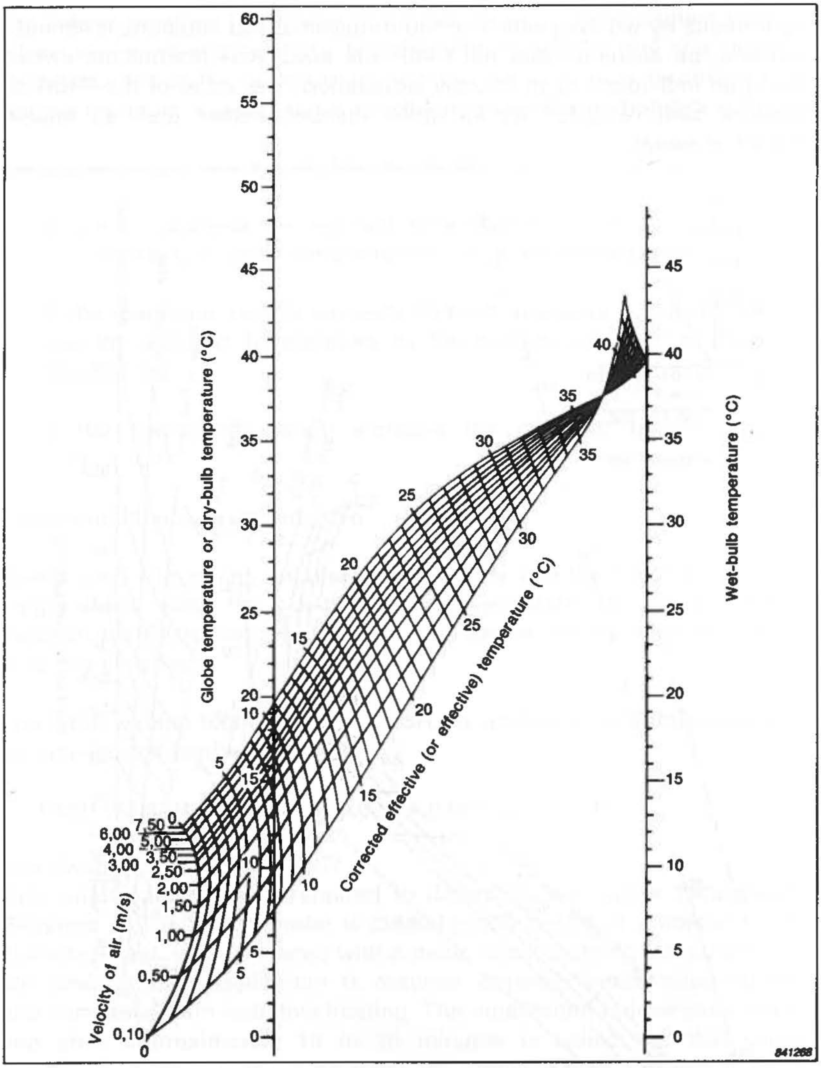

Fig. 3. The "normal" Effective Temperature scale, appropriate for light clothing. This scale is also used for Corrected Effective Temperature Index. To use the nomogram, draw a line connecting the dry- and wet-bulb temperatures. The CET is given by the intersection of the line and the appropriate CET line

experiments by working with a group of acclimatized subjects. It cannot, therefore, be assumed that the P4SR will accurately predict the sweat rate of an individual, or of another population. The value of the P4SR is therefore best regarded as an index number, rather than an actual amount of sweat.

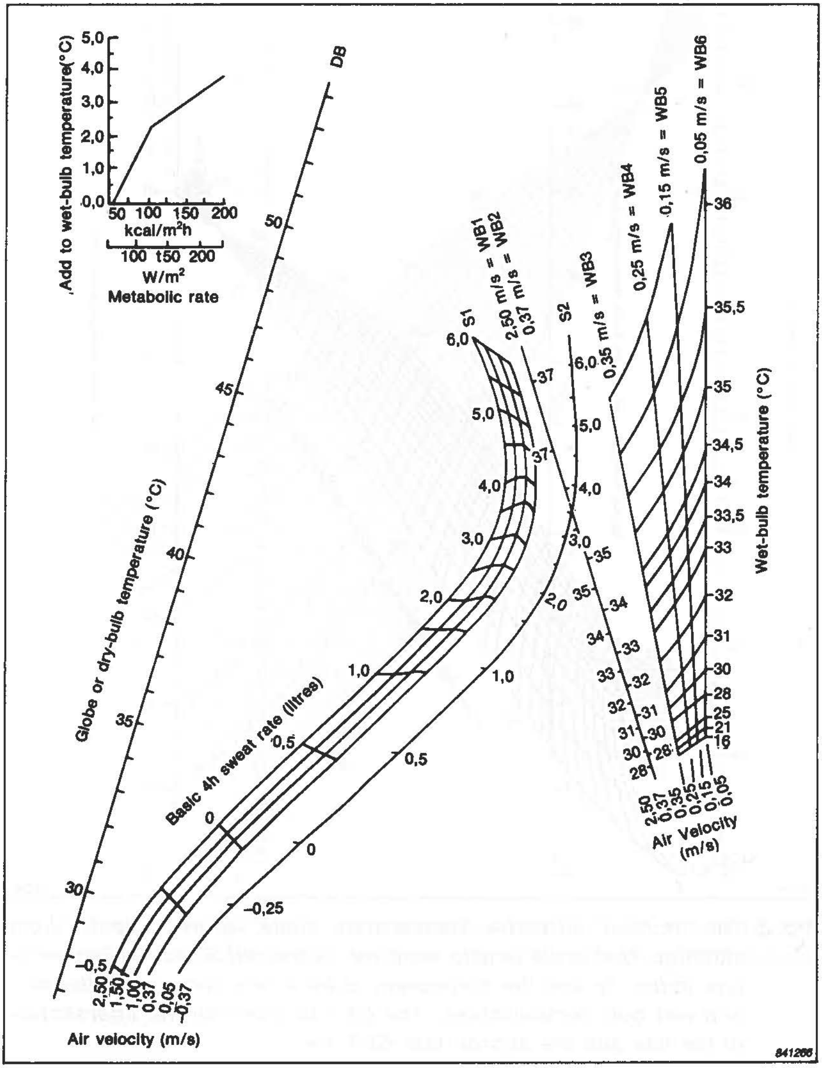

Fig. 4. Nomogram for calculating P4SR. The method of use is explained in the text

The index combines the effects of air temperature, mean radiant temperature, air speed and humidity, together with metabolic rate and clothing insulation. The index is empirical and has no analytical formulation. It may be found for a given set of conditions using the nomogram in Fig.4.

Several steps are required to find the P4SR.

1. If $t_g \neq t_a$, increase the wet-bulb temperature by 0,4 $(t_g - t_a)$ °C.
   where, t_g = globe temperature t_a = air temperature.

2. If the metabolic rate M exceeds 63 W/m^2 (sedentary activity), increase the wet-bulb temperature by the amount indicated in the inset chart (Fig.4).

3. If the men are clothed, increase the wet-bulb temperature by 1,4 I_{clo}(°C).

These modifications are additive.

Now draw a line joining the globe temperature and the modified wet-bulb temperature, using the wet-bulb scale appropriate for the air speed. Read off the Basic Four-Hour Sweat Rate (B4SR) on the scale appropriate to the air speed.

The P4SR is then found from the B4SR, by adding an amount dependent on activity and clothing.

$$\text{P4SR} = \text{B4SR} + 0{,}37\,I_{clo} + (0{,}012 + 0{,}001\,I_{clo})\,(M - 63)$$

Wet Globe Temperature (WGT)

Only one temperature is required to determine wet globe temperature [Botsford, 13]. A thermometer is placed in the centre of a hollow 2 1/2-in diameter black globe covered with a damp black cloth. When placed in a hot environment, equilibrium is reached between evaporative cooling and convective and radiative heating. The equilibrium temperature obtained after approximately 10 to 15 minutes is called the Wet Globe Temperature (WGT). This is probably the simplest index to determine. A version of this device (Botsford's ball) which contains a self-feeding water reservoir is shown in Fig.5.

The Wet Bulb Globe Temperature Index (WBGT)

The index was originally established in the 1950's to provide the Navy with a method for judging the severity of the thermal environment and

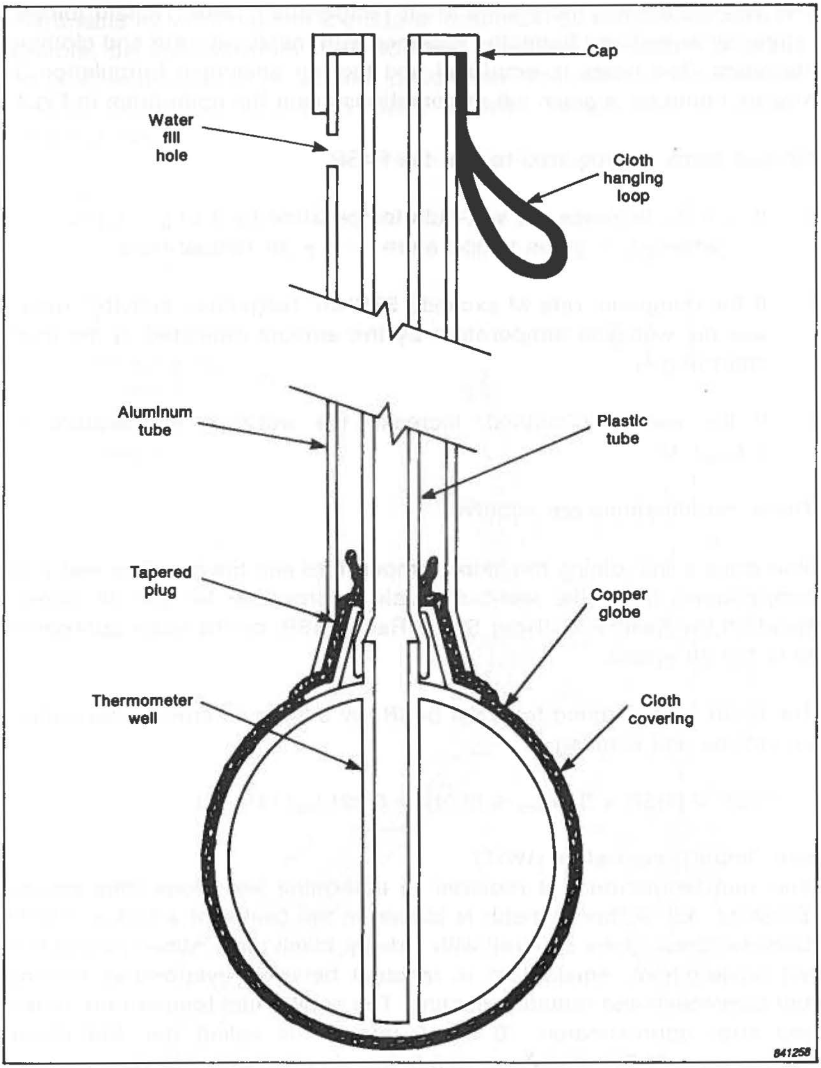

Fig. 5. Sectional sketch showing construction of a Wet Globe Thermometer (not to scale)

the risk of heat casualties when performing exercise and training [Yaglou & Minard, 20].

The transducers which are discussed in the next section were selected because they responded to the same environmental factors as a human being. From the research performed, the combination of parameters that was best related to the human response was found to be:

$$WBGT = 0{,}7 \cdot t_{nw} + 0{,}3 \cdot t_g \qquad \text{(units in °C or °F)}$$

where, t_{nw}= natural wet bulb temperature
and t_g = globe temperature.

However, it was found that in direct sunlight, the black globe overestimated the influence of the radiation. A third transducer, for measuring air temperature (t_a) was therefore introduced. In this case the measured values are combined in the following manner:

$$WBGT = 0{,}7\, t_{nw} + 0{,}2\, t_g + 0{,}1\, t_a$$

This equation is very similar to the first equation with the exception that the influence of the globe temperature on the index is reduced.

When the *WBGT*-index has been measured, the value can be compared with recommended limit values, which can be seen in Table 4 (from ISO 7243). As seen in the table these limits are dependent on the activity level and on the state of acclimatization. A list of the different activity levels and examples of the type of activity are shown in Table 5. The *WBGT*-index and its use will be described in greater detail in the following chapter of this article.

Analytical heat stress indices

The Heat Stress Index (HSI)

The Heat Stress Index (HSI) was developed at the University of Pittsburgh by Belding and Hatch in 1955 [14]. It is based on a model of heat exchange which assumes a constant skin temperature of 35°C. Within the evaporative heat regulation zone it is assumed that the required rate of sweating E_{req} is equal to the metabolic heat production (M) less the heat loss by radiation (R) and convection (C).

$$E_{req} = M - R - C$$

No distinction is made between metabolic heat production and the energy required to perform work, and respiratory heat loss is ignored. The maximum evaporative loss which can occur is denoted by E_{max}. The heat stress index is defined as the ratio:

$$HSI = (E_{req} / E_{max}) \times 100$$

An upper limit of 390 W/m² is assigned to E_{max}; this corresponds to a sweat rate of 1 litre/h for a typical man. This was taken to be the maximum sweat rate that can be maintained over a period of 8 hours. The calculation procedures are shown in Table 2.

A *HSI* of 100 represents the upper limit of the **prescriptive zone**, i.e. the zone where the body is in thermal equilibrium. If $E_{req} > E_{max}$ the body cannot maintain equilibrium and body temperature begins to rise. Many industrial working situations come into this category. Although work may be carried out for a limited period in such an environment, prolonged work is not possible. Exposure must be terminated before the heat accumulated in the body causes the deep body temperature to rise to a dangerous level. Belding and Hatch took 1,8°C as the maximum permissible rise in body temperature, corresponding to an additional heat storage in an average man of 264 *kJ*. It is then possible to calculate the allowable exposure time (AET) from the formula in Table 2.

The interpretation of *HSI* is shown in Table 3, which is an abbreviated version of the table given by Belding and Hatch [14].

The *HSI* is an index which can easily be expressed in terms of the environmental variables. This has the considerable advantage that the effect of changing any of the variables can easily be estimated.

		Clothed	**Unclothed**
Radiation loss	$R\ (W/m^2)$	$4{,}4\ (35 - t_r)$	$7{,}3\ (35 - t_r)$
Convection loss	$C\ (W/m^2)$	$4{,}6\, v^{0{,}6} (35 - t_a)$	$7{,}6\, v^{0{,}6} (35 - t_a)$
Max.evaporative loss	$E_{max} (W/m^2)$	$7\, v^{0{,}6} (56 - p_a)$	$11{,}7\, v^{0{,}6} (56 - p_a)$
		(upper limit of 390 W/m^2	
Required sweat loss	$E_{req} (W/m^2)$	$E_{req} = M - R - C$	
Heat stress index	*HSI*	$HSI = E_{req} / E_{max} \times 100$	
Allowable exposure time	*AET* (min)	$ET = 2440 / (E_{req} - E_{max})$	

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Table 2. Equations for estimating the Heat Stress Index (HSI) and the Allowable Exposure Time (AET)

HSI	Effect of eight-hour exposure
-20	Mild cold strain
0	No thermal strain
10-30	Mild to moderate heat strain. Little effect on physical work, but possible decrement on skilled work
40-60	Severe heat strain, involving threat to health unless physically fit. Acclimatisation required
70-90	Very severe heat strain. Personnel should be selected by medical examination. Ensure adequate water and salt intake
100	Maximum strain tolerated by fit acclimatised young men
Over 100	Exposure time limited by rise in deep body temperature

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Table 3. Interpretation of Heat Stress Index

The Index of Thermal Stress (ITS)
The index of thermal stress (ITS) was introduced by Givoni in 1963 [15]. It combines some of the advantages of the P4SR and of the *HSI*. The derivation of ITS owes its form to that of the *HSI*, but as with the P4SR the measure of strain used is the sweat rate. The result is that the ITS has an analytical form, which can be evaluated on a calculator and manipulated to demonstrate the effect of changing the environmental variables. The use of sweat rate as the measure of environmental stress is more fundamental than the wettedness ratio (i.e. E_{req}/E_{max}) used by the *HSI*.

The derivation starts with the basic heat loss equation:

$$E_{req} = H - (C + R) - R_s$$

where the usual notation is used and R_s is the solar load. The metabolic free heat production H is used to give greater accuracy when external work is performed. In the prescriptive zone, where the body is in thermal equilibrium, actual sweat rate S_w, measured in equivalent W/m^2, is in general greater than E_{req}. This is because both the secretion and the evaporation of sweat occur unevenly over the body. So some parts of the body become completely wet and lose sweat by dripping, before the rest of the body is completely wet. The efficiency of sweating is expressed quantitatively using the term by η_{sc}, and therefore the actual sweat rate is given by the equation:

$$S_W = E_{req} / \eta_{sc}$$

The efficiency of sweating η_{sc} depends on E_{req} / E_{max}, where E_{max} depends on the air velocity and the water vapour pressure in the ambient air. Substituting the basic heat loss equation for E_{req} gives the formula for ITS (units in g/hr), which is a prediction of the sweating rate.

$$ITS = \left(H - (R + C) - R_s \right) / (0{,}37\, \eta_{sc})$$

The factor 0,37 converts the sweat rate from W/m^2 into g/hr for an average man.

This formula is relatively straightforward to compute, particularly on a programmable calculator. The detailed formulae for estimating the dry heat loss ($R + C$, radiation + convection), effect of sunshine (R_s), maximum evaporation (E_{max}) and efficiency of sweating (η_{sc}) are not included. But by knowing the air temperature, mean radiant temperature, air velocity, water vapour pressure (humidity), activity level and clothing the ITS – index may be calculated.

New Effective Temperature (ET)*
This index should not be confused with the empirical indices ET or CET described earlier. The new Effective Temperature is an analytical temperature index based on the heat balance equation for a human being (Gagge et al. [16]).

The ET* index combines the influence of activity, clothing, air temperature, mean radiant temperature, air velocity and humidity. For an actual environment, the ET* may be calculated knowing the above 6 factors. The thermal stress of ET* in the actual situation is then the same as the thermal stress on a sedentary person, dressed in 0,6 clo, and exposed to 50% relative humidity and an equivalent temperature equal to ET*.

This index is rather difficult to describe without writing a whole paper. At this stage it is enough to know that it is based on the heat balance equations and it includes all 6 factors.

Required Sweat Rate Index (SR)
The Required Sweat rate is an analytical index, which now is being proposed by ISO as a Draft Standard ISO/DIS 7933. This index should be a supplement to the more simple *WBGT*-index, when a more detailed analysis is needed. This method is in principle very similar to the method used in the ITS-index. Based on the heat balance equation for the human body the required sweating for thermal equilibrium is estimated.

First the necessary equation (E_{req}) is estimated from:

$$E_{req} = M - W - C - R$$

This can be calculated by knowing the metabolic rate (M, W), thermal insulation of the clothing (I_{cl}), air temperature (t_a), air velocity (v_a) and mean radiant temperature ($\bar{t}_r$). Then the heat loss by radiation (R) and convection (C) may be calculated.

The maximum evaporation (E_{max}), which can be absorbed by the environment, is estimated by the equation:

$$E_{max} = (p_{sk,s} - p_a) / R_e$$

where

$p_{sk,s}$ = saturated water vapour pressure at the skin ($\sim 5{,}9\,kPa$)

p_a = water vapour pressure in the environment (kPa)

R_e = water vapour resistance of the clothing ($m^2\,kPa\,/\,W$)

Based on the required evaporation (E_{req}) and the maximum evaporation (E_{max}) it is then possible to estimate the following factors:

Required skin wettednes	$w_{req} = E_{req} / r$
Required sweat rate	$SW_{req} = E_{req} / r$
Sweating efficiency	$r = 1 - 0{,}5 \cdot e^{-6{,}6(1 - w_{req})}$

Dependent on the physiological limitations to factors such as sweat rate, total sweat loss, heat storage and skin wettedness, which are listed in Table 1, it is possible to evaluate if continuous work is acceptable. If not there are procedures for calculating the accepted working time.

As for other analytical indices it is necessary to know the activity level, clothing (thermal insulation, water vapour resistance) and the four environmental parameters (air temperature, mean radiant temperature, air velocity, humidity). This method is described by Vogt et. al [17, 18].

WBGT-Heat stress index

The International Standard ISO 7243, which was published in 1982, is based on using the *WBGT*-index for evaluation of hot working environments.

This is the first time that an agreed International Standard on heat stress is accepted. Before publication of the ISO standard, this index had already been used in several countries and in many different workplaces. It has been especially widely used in the USA and TLV's (**T**hreshold **L**imit **V**alues) have been established by ACGIH (**A**merican **C**onference of **G**overnment and **I**ndustrial **H**ygienists), [19]. In many other countries the *WBGT*-index has also been recommended by the local Occupational Safety and Health Associations. The index was originally established to provide the Navy with a method for judging the severity of the thermal environment and the risks for heat casualties, when performing exercise and training. The transducers which are discussed in the next section were selected because they responded to the same environmental factors as a human being (air temperature, mean radiant temperature, air velocity, humidity). The combination that was best related to the human response was found to be:

$$WBGT = 0{,}7\, t_{nw} + 0{,}3\, t_g$$

where t_{nw} = natural wet bulb temperature (°C, °F)
t_g = standard globe temperature (°C, °F)

In direct sunlight, it was found that the black globe overestimated the influence of the radiation and therefore a third transducer for measuring air temperature, t_a was introduced. In this case the measured values should be combined in the following way:

$$WBGT = 0{,}7\, t_{nw} + 0{,}2\, t_g + 0{,}1\, t_{ta}$$

where t_a = air temperature (°C, °F)

The background for using the *WBGT*-index has been well described in literature, since the index was introduced in the 1950's [21, 22, 23, 24]. This index is therefore well known to those dealing with hot environments.

When the *WBGT*-index has been measured, the value can be compared with the recommended limit values, which can be seen in Table 4 (from ISO 7243). As seen in the table these limits are dependent on the activity

Metabolic rate class	Metabolic rate, M		Reference value of WBGT			
	Related to a unit skin surface area W/m²	Total (for a mean skin surface area of 1,8 m²) W	Person acclimatized to heat °C		Person not acclimatized to heat °C	
0 (resting)	$M < 65$	$M < 117$	33		32	
1	$65<M<130$	$117<M<234$	30		29	
2	$130<M<200$	$234<M<360$	28		26	
3	$200<M<260$	$360<M<468$	No sensible air movement 25	Sensible air movement 26	No sensible air movement 22	Sensible air movement 23
4	$M>260$	$M>468$	23	25	18	20

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Table 4. Reference values for WBGT for different metabolic rates. Examples of type of activity in the different classes are given in Table 2 (after ISO 7243)

level and on the state of acclimatization. A listing of the different classes of activities are shown in Table 5.

The limits recommended in Table 4 are based on an acceptable increase in deep body temperature of less than 1°C, i.e. from 37 to 38°C. As indicated in the first chapters, there are however great individual differences in the tolerance to hot work environments. So the recommended limits are set so that in a normal group of people only very few may have problems by working under these conditions. In such a group there may be several persons, who can tolerate even a higher level of heat stress; but then it is recommended only to continue the work under special precautions.

As the body temperature reacts rather slowly to changes in the thermal environment and the same is the case for the transducers (natural wet bulb, globe), the measurement of the *WBGT*-index and the estimation of the activity level (Tables 4 and 5) should be based on 1 hour mean values.

The transducers

When measuring the *WBGT*-index three transducers are needed (Fig.6) to measure: Globe temperature, natural wet bulb temperature and air temperature.

Class	Metabolic rate range, *M*		Value to be used for calculation of mean metabolic rate		Examples
	related to a unit skin surface area W/m²	for a mean skin surface area of 1,8 m² W	W/m²	W	
0 Resting	$M<65$	$M<117$	65	117	Resting
1 Low metabolic rate	$65<M<130$	$117<M<234$	100	180	**Sitting at ease:** light manual work (writing, typing, drawing, sewing, book-keeping); hand and arm work (small bench tools, inspection, assembly or sorting of light materials); arm and leg work (driving vehicle in normal conditions, operating foot switch or pedal). **Standing:** drill (small parts); milling machine (small parts); coil winding; small armature winding; machining with low power tools; casual walking (speed up to 3,5 km/h).
2 Moderate metabolic rate	$130<M<200$	$234<M<360$	165	297	Sustained hand and arm work (hammering in nails, filling); arm and leg work (off-road operation of lorries, tractors or construction equipment); arm and trunk work (work with pneumatic hammer, tractor assembly, plastering, intermittent handling of moderately heavy material, weeding, hoeing, picking fruit or vegetables); pushing or pulling lightweight carts or wheelbarrows; walking at a speed of 3,5 to 5,5 km/h; forging.
3 High metabolic rate	$200<M<260$	$360<M<468$	230	414	Intense arm and trunk work; carrying heavy material; shovelling; sledge hammer work; sawing, planing or chiselling hard wood; hand mowing; digging; walking at a speed of 5,5 to 7 km/h. Pushing or pulling heavily loaded handcarts or wheelbarrows; chipping castings; concrete block laying.
4 Very high metabolic rate	$M>260$	$M>466$	290	522	Very intense activity at fast to maximum pace; working with an axe; intense shovelling or digging; climbing stairs, ramp or ladder; walking quickly with small steps, running, walking at a speed greater than 7 km/h.

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Table 5. Classification of levels of metabolic rate (after ISO 7243)

Natural wet bulb transducer

Because sweating is an important factor in the heat exchange between a human being and the environment, a transducer which simulates evaporative heat loss is required. The easiest way to achieve this is to cover the bulb of a normal mercury thermometer with a wet cotton sock (or wick). The evaporation of water from this wick cools the sensor in the same way as evaporation of sweat cools the human body. Thus, the

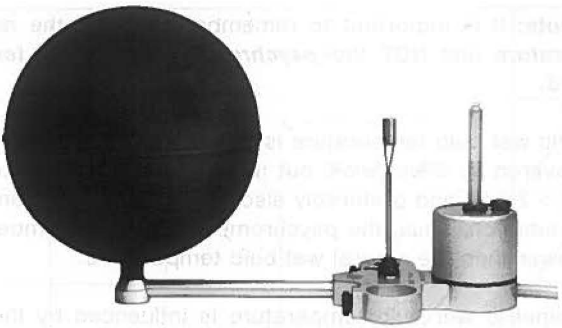

Fig. 6. WBGT Transducers

temperature of this sensor, the natural wet bulb temperature (*t_{nw}*), is most of the time lower than the air temperature. Because the measured natural wet bulb temperature will be influenced by the size and construction of the sensor the requirements have been described in detail in ISO 7243 as follows:

a) Shape of the sensitive part of the sensor: cylindrical
b) External diameter of the sensitive part of the sensor: 6 ± 1 mm
c) Length of the sensor: 30 ± 5 mm
d) Measuring range: 5 to 40°C
e) Accuracy of measurement: ± 0,5°C
f) The whole sensitive part of the sensor shall be covered with a white wick of a highly water-absorbant material (for example cotton).
g) The support of the sensor should have a diameter equal to 6 mm and 20 mm of it should be covered by the wick to reduce conduction from the support to the sensor
h) The wick should be woven in the shape of a sleeve and should be fitted over the sensor precisely. Too tight or too loose a grip is detrimental to the accuracy of measurement. The wick should be kept clean.
j) The lower part of the wick should be immersed in a reservoir of distilled water. The free length of the wick in the air should be 20 to 30 mm
k) The reservoir should be designed in such a way that the temperature of the water inside cannot rise as a result of radiation from the atmosphere.

Important Note: It is important to remember that it is the ***natural wet bulb temperature*** and **NOT** the ***psychrometric wet bulb temperature*** which is used.

Psychrometric wet bulb temperature is also measured with a temperature sensor covered by a wet wick; but the sensor is exposed to a forced air velocity (> 2 m/s) and preferably also shielded from any environmental thermal radiation. Thus, the psychrometric wet bulb temperature will always be lower than the natural wet bulb temperature.

The psychrometric wet bulb temperature is influenced by the humidity and air temperature of an environment. It is often used, together with air temperature, to measure relative humidity or water vapour pressure. On the other hand, natural wet bulb temperature is influenced by air temperature, air velocity, radiant temperature and humidity of the environment. Especially at low air velocities and high radiant levels there is a significant difference between the two values.

The difference between the natural wet bulb temperature and the psychrometric wet bulb temperature is influenced by the radiant temperature, air temperature, air velocity and humidity - series of curves giving these relations are shown in Fig.7 for one air temperature level. The curves are based on equation from Malchaire [25]. A connection from psychrometric wet bulb to natural wet bulb can then only be performed when air temperature, globe temperature and air velocity are also known.

Globe Temperature

A globe thermometer is used to account for the heat exchange due to radiation. The standard globe is a radiantly black, hollow 0,15 m (6 inches) diameter sphere normally made of copper. The globe temperature (t_g) is the temperature at the centre of the sphere, which is equal to the mean surface temperature of the sphere. Globe temperature is influenced by air temperature, radiant temperature and air velocity.

The specifications for the globe-sensor are in ISO 7243 as follows:

a) Diameter: 150 mm.
b) Mean emission coefficient: 0,95 (matt black globe).
c) Thickness: as thin as possible.
d) Measuring range: 20 to 120°C.
e) Accuracy of measurement
    - range 20 to 50°C: ± 0,5°C;
    - range 50 to 120°C: ± 1°C.

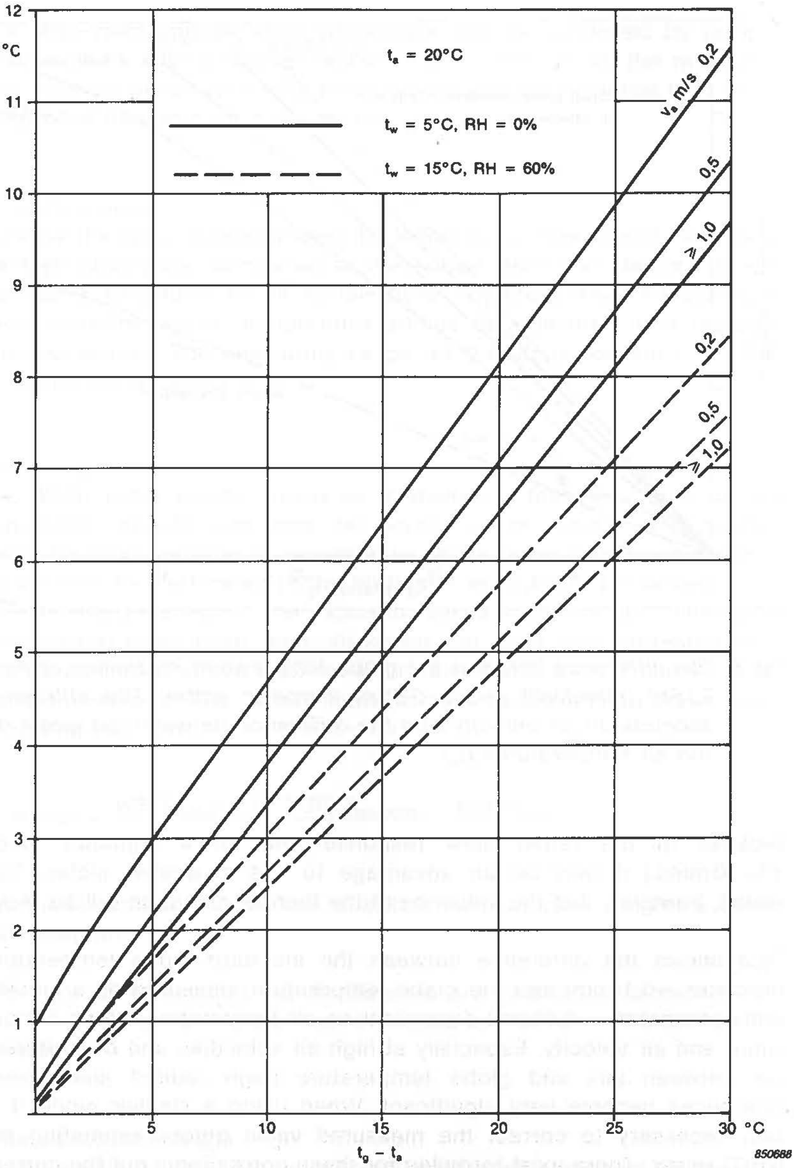

Fig. 7. Diagram to estimate the difference between natural wet bulb temperature, t_{nw} and psychrometric wet bulb temperature, t_w. The difference depends on air temperature, t_a, air velocity, v_a, temperature radiation, t_g and humidity level

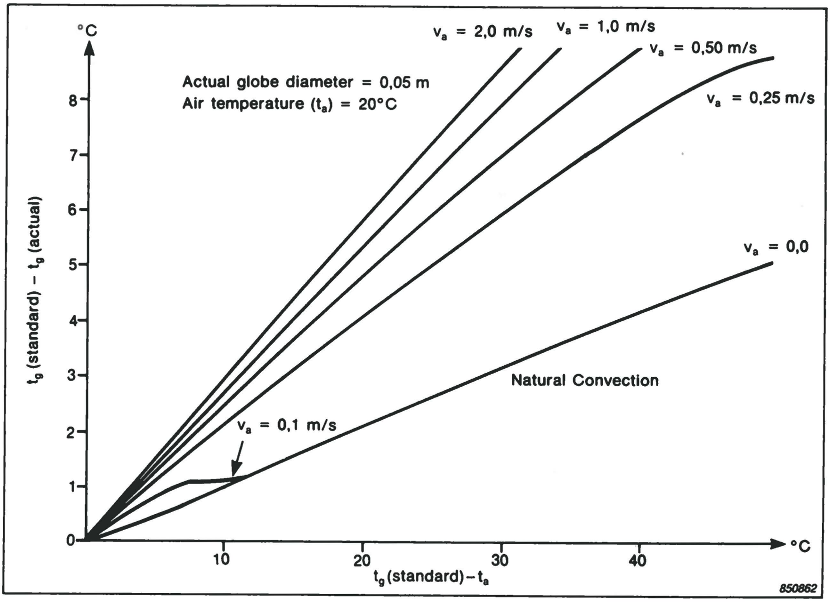

Fig. 8. The difference between the globe temperature measured using a 0,15 m (standard) and a 0,05 m diameter globe. The difference depends on air velocity and the difference between the globe (t_g) and air temperatures (t_a)

Because of the rather slow response time of a standard globe (10−30 mins.) it may be an advantage to use a smaller globe. This means, however, that the influence of the thermal radiation will be less.

Fig.8 shows the difference between the standard globe temperature (diameter = 0,15 cm) and the globe temperature measured by a smaller globe (diameter = 0,05 cm) dependent on air temperature, globe temperature and air velocity. Especially at high air velocities and big differences between air- and globe temperature (high radiant load) these differences become very significant. When using a smaller globe it is then necessary to correct the measured value before estimating the *WBGT*-index. There exist formulae for these corrections; but the corrections can **only** be made when air temperature and air velocity are known.

It is also questionable what advantages can be achieved by using a smaller globe with a shorter response time. First of all the measuring time must be based on 1 hour mean values and the response time of the deep body temperature is not so fast.

Air Temperature

Because the globe overestimates the influence of direct sunshine, due to the high absorption compared to the human skin and clothing, it was decided to introduce the air temperature. Therefore when measuring in direct sunshine the air temperature should be measured by a radiantly shielded sensor. The measuring range for the air temperature is 10 to 60°C and the accuracy ± 1°C.

Measuring positions

The *WBGT*-index should always be measured at the work place, i.e. the transducers should substitute the person or be placed at a position where the heat exposure is assumed to be the same. The measurements should then be performed in the abdomen level (0,6 m for seated, 1,1 m for standing persons). If the exposure varies significantly it should be measured at three levels: feet, abdomen and head. This corresponds to 0,1; 0,6 and 1,1 m above floor level for seated and 0,1; 1,1 and 1,7 m for standing persons. The *WBGT*-index is then based on the mean value according to:

$$WBGT = \frac{WBGT_{head} + 2 \cdot WBGT_{abdomen} + WBGT_{feet}}{4}$$

The measurement at abdomen level has then a higher weighting factor than head and feet.

It is very important that the transducers are positioned in such a way that they are not screened from the radiation, which will influence the workplace.

Time weighted average

During a working day both the thermal environment and also the place of work for a person may change. The *WBGT*-index should then be based on a time weighted average with a 1 hour time basis:

$$WBGT = \frac{t_1 \cdot WBGT_1 + t_2 \cdot WBGT_2 + ...t_n \cdot WBGT_n}{t_1 + t_2 + ... + t_n}$$

where

$WBGT_n$ = $WBGT$ determined for situation n

t_n = time spent at situation n

$\Sigma t_n = 1$ hour

$$WBGT = \frac{20 \times 28°C + 20 \times 28°C + 20 \times 20°C}{20 \times 20 \times 20} = 25{,}3°C$$

When determing the corresponding exposure limit according to Table 4 it is also necessary to estimate a time weighted average for the activity level.

This method of applying time weighted average values may also be used, when planning a work-rest schedule. An example is shown in Fig.9. The curves show the relation between the time weighted average metabolic rate and the acceptable exposure limit for acclimatized person exposed to air movement which can be sensed (Table 4). It is here assumed that the person is resting at the same workplace, i.e.that the *WBGT*-index is the same when working and when resting. The curves can be estimated from Table 4 and the use of time weighted average of the metabolic rate.

When the person is resting in an environment with another *WBGT*-value this has to be taken into account as shown in the following example:

Example:

A person acclimatized to heat works according to the following schedule:

Time	Metabolic rate	*WBGT*
20 min.	230 W/m^2	28°C
20 min.	165 W/m^2	28°C
20 min.	65 W/m^2	28°C

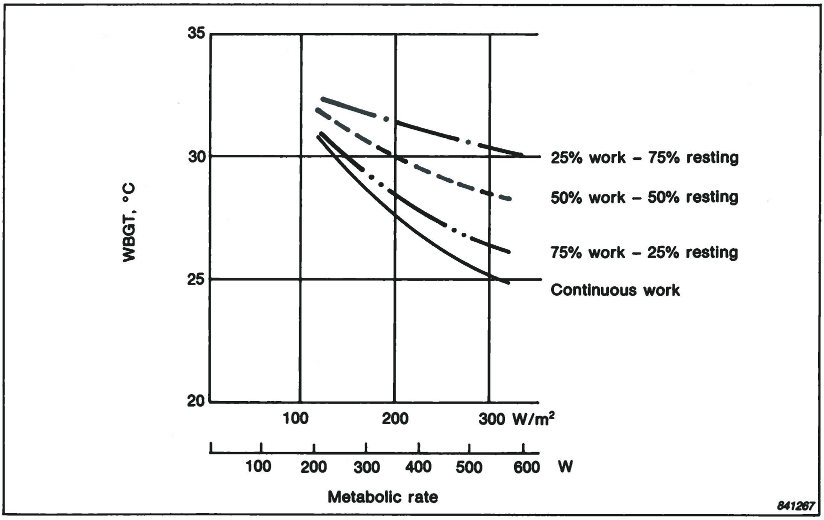

Fig. 9. Curves showing reference values of WBGT established for various work/rest cycles. The curves plotted assume that the WBGT value at the resting place is equal to the WGBT value at the workplace (time base equal to 1 h; sensible air movement; person aclimatized to heat). These curves may facilitate the reorganisation of the work by changing the work/rest cycles. After ISO 7243 Annex. B.

The time weighted average of the metabolic rate is then:

$$M = \frac{230 \times 20 + 165 \times 20 + 65 \times 20}{20 + 20 + 20} = 153\ W/m^2$$

This corresponds to class 2 in Table 5 and the acceptable exposure limit is then 28°C. This is exactly the same as the *WBGT* measured at the workplace.

Now if instead the person is resting (65 W/m^2) in another environment with $WBGT = 20°C$ the *WBGT*-index for this person will be

$$WBGT = \frac{20 \times 28°C + 20 \times 28°C + 20 \times 20\,°C}{20 \times 20 \times 20} = 25{,}3°C$$

This is lower than the limit 28°C. At this *WBGT* value (25,3°C) a time weighted average metabolic rate equal to class 3 can be accepted.

The selection of place and time for the measurement of the environmental conditions is very important. The worst situation from the point of view of heat stress must be evaluated. If the process changes, it must be studied carefully so as to determine the worst conditions. If the process is constant, the hottest part of the day must be evaluated. This often coincides when the outdoor temperature and/or sunload is the highest. The evaluation of the worst conditions should be made, as mentioned before, on the basis of a 1 hour mean value for the *WBGT*-index.

The best solution is often to measure a whole working period/day (i.e. 4–8 hours) and then afterwards study the changes by estimating mean–, maximum– and minimum values, and maximum 1 hour mean value for the *WBGT*-index. Fig.10 shows a 4-hour measurement of the *WBGT*-index with indication of the above mentioned statistical values. These values are all determined automatically by using the new 1219 *WBGT*-Heat Stress Monitor from Brüel & Kjær. The instrument also displays at what time the 1-hour period with the highest heat stress started. This feature facilitates the measurement significantly.

Conclusion

There is no heat stress index developed to date, which provides the true answer to the evaluation of heat stress in all situations. When all factors which influence man's response to heat are considered, there will always be a certain degree of inaccuracy when predicting individual situations.

Besides being used for predicting man's response to hot environments a heat stress index may also be used for comparisons between situations;

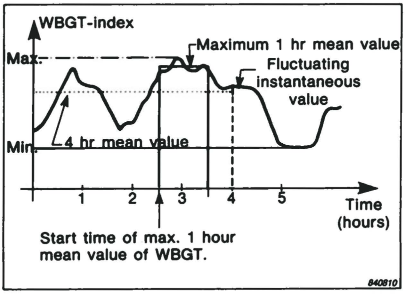

Fig. 10. 4-hour measurement of the WBGT-index showing maximum-minimum- mean- and the 1 hour maximum mean value

as for instance before and after implementation of a new process or devices which should reduce the level of heat stress.

Even if the *WBGT*-index may have its limitations, it is an index which has been widely used and considerable experience has been gained. As a screening index it is very useful. Whenever dealing with a hot workplace it is recommended that the workplace should always be mapped using the *WBGT*-index. Only at places where the index values are above or close to the recommended limit values it may then be necessary with a more detailed analysis. This could then be made by using the Required Sweat Rate index.

Whenever a threshold or limit value has been set it should be used carefully and with common sense. Exceeding a limit value does not necessarily indicate catastrophe or that all work should be stopped. It just implies that it is necessary to take some precautions when continuing the work. Often it will just be a matter of changing the work-rest schedules or to plan the work so that the work with the highest activities is not performed at the time of the day when the heat stress is highest.

With the international standardization and better measuring instrumentation a more uniform evaluation of hot workplaces should be hopefully possible in the future.

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A NEW THERMAL ANEMOMETER PROBE FOR INDOOR AIR VELOCITY MEASUREMENTS

by

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ABSTRACT

In this article a new hot film anemometer probe for indoor climate investigations is described. Due to its innovative design principles, this probe is ideally suited for measuring low air velocities in indoor spaces. A discussion of all the physical parameters influencing the measuring accuracy is given, and in addition new equipment for testing low velocity anemometers is described.

SOMMAIRE

Cet article décrit une nouvelle sonde anémométrique à film chaud pour les études d'ambiances thermiques intérieures. Grâce à sa conception entièrement nouvelle, cette sonde convient parfaitement aux mesures des faibles vitesses d'écoulement d'air dans les espaces intérieurs. Tous les paramètres physiques influençant la précision de la mesure y sont discutés et on y trouve également la description des tests d'anémomètres pour faibles vitesses d'air.

ZUSAMMENFASSUNG

Dieser Artikel stellt eine neue Heiß-Film-Anemometer-Sonde vor. Mit ihr soll das Raumklima beurteilt werden. Durch fortschrittliche Konstruktion eignet sich diese Sonde ideal zur Messung niedriger Luftgeschwindigkeiten in Räumen. Alle physikalischen Parameter, die die Meßgenauigkeit beeinflussen, werden diskutiert. Darüberhinaus werden neue Geräte zur Prüfung von Anemometern für niedrige Luftgeschwindigkeiten vorgestellt.

1. Introduction

The Brüel & Kjær Indoor Climate Analyzer Type 1213 is a microprocessor based measuring instrument dedicated to the measurement of all the physical parameters necessary to make a thorough evaluation of the thermal environments for people in indoor spaces.

Complaints against the indoor climate very often concern draught. Therefore, an evaluation of the indoor climate should always include measurement and analysis of air velocity in order to find the underlying causes of the problems.

An article describing the influence of air velocity and other relevant parameters on thermal comfort, and how to measure them, appeared in an earlier issue of Technical Review ("Local Thermal Discomfort" B & K *Technical Review*, No.1 – 1985). The present article will discuss the construction and performance of the new B & K Air Velocity Transducer Type MM 0038, which is one of the five transducers used in connection with the Indoor Climate Analyzer.

With its untraditional design, combining convenience in use with high accuracy, this transducer may well set a new trend in transducer technology.

Requirements for the Transducer

For measuring indoor air velocities in a range which has influence on thermal comfort, the transducer had to meet the following requirements:

1) It should be sensitive enough to detect the lowest air velocities that can be perceived by human beings.
2) It should have fast response, as fluctuating air velocities reduce comfort.
3) It should be omnidirectional, i.e. have the same sensitivity for air flow from all directions, since the direction of the indoor air velocity is in most cases unknown and variable.
4) Finally, it should be sufficiently sturdy so that it can be moved around from place to place several times a day, without any risk of being damaged.

Choice of Measuring Principle

A number of different physical principles can be utilized for measuring air velocity. However, the requirement for omnidirectionality combined with high sensitivity at low velocities indicated the **thermal** anemometer to be the best solution. With this type of anemometer the air velocity is determined as a function of the forced convective heat loss from a small heated body. By proper choice of geometrical shape, material and heating rate it is possible to construct a probe which meets all the above requirements.

Description of the B & K Air Velocity Transducer Type MM 0038

A long series of experiments at the Brüel & Kjær development department has resulted in a hot film anemometer probe of an entirely revolutionary design. Some of the design criteria will be discussed later in this article.

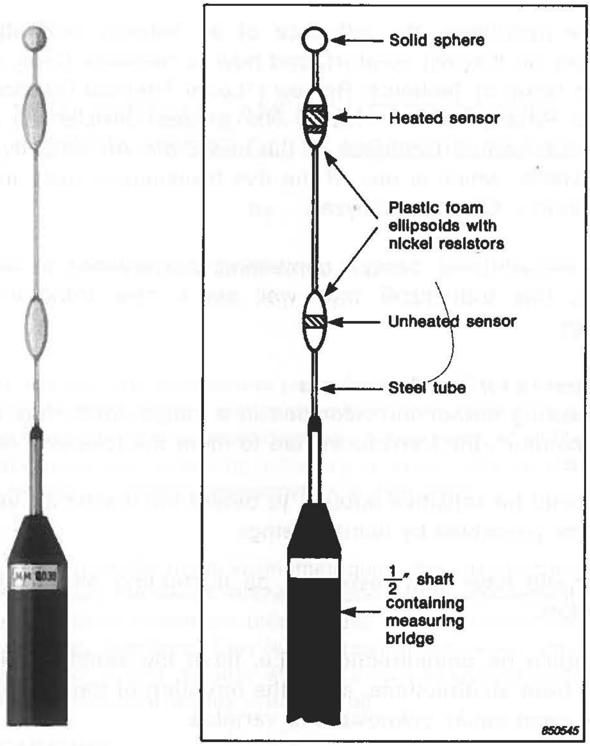

Fig. 1. The B & K Air Velocity Transducer Type MM 0038

As shown in Fig.1 the probe consists of two wirewound nickel resistance thermometers wound on ellipsoidal cores made of a highly thermal insulating foam material, ground to shape and supported by a thin stainless steel tube.

The upper ellipsold carries three coils of electrically heated nickel wire; the lower has one unheated coil acting as an air temperature reference. The coils are wound in a single layer without any space between the windings, and they are finally protected by a thin layer of white epoxy enamel. Thin copper leads passing through the supporting tube connect the two sensors to a measuring bridge on a printed circuit board in the shaft.

The resistance and temperature coefficient of the nickel wire are extremely stable and well defined, making it possible to produce fully interchangeable transducers.

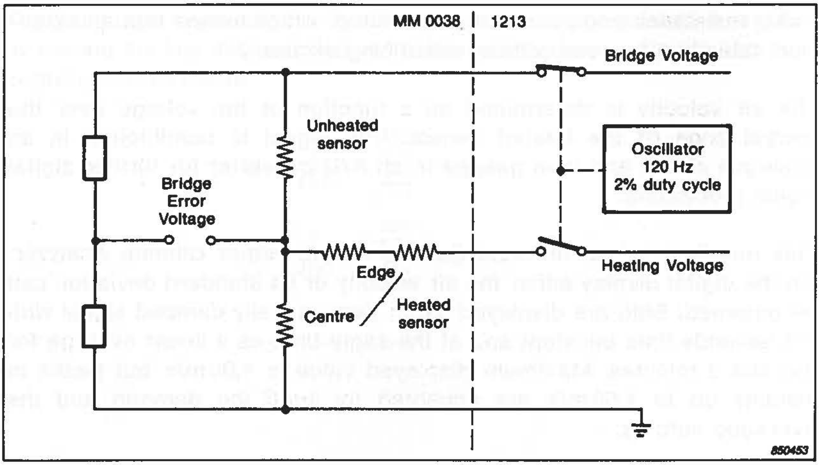

Fig. 2. Simplified diagram of the transducer circuit

Fig.2 shows a diagram of the measuring bridge, which, together with a servo system in the Indoor Climate Analyzer, controls the heating rate in such a way that a constant temperature difference is maintained between the two ellipsoidal sensors. Two important advantages are gained from controlling the sensor temperature in this manner: Variations in air temperature will cancel out and the transducer's response to a sudden change in air velocity is much faster than the thermal resonse of the sensors.

To avoid an excessive temperature increase in the lower sensor and to obtain the greatest accuracy in determining the actual deviation from correct temperature difference, the servo system is operated in pulse mode. The error voltage across the bridge is measured in short pulses, during which the heating voltage is switched off. Subsequently, the measured error voltage is amplified, stored in a sample-and-hold circuit and then passed to a small switch-mode power supply, which controls the heating voltage.

In view of the battery power supply the whole circuit is designed for minimum power consumption.

As a special feature, only the central zone of the heated sensor is incorporated in the measuring bridge. This gives a considerably shorter response time, due to the more uniform temperature distribution on this part of the heated surface.

Cable resistance compensation is provided, which means that an extension cable can be used without sacrificing accuracy.

The air velocity is determined as a function of the voltage over the central zone of the heated sensor. The signal is conditioned in an analogue circuit and then passed to an A/D converter for further digital signal processing.

This results in seven different outputs on the Indoor Climate Analyzer: On the digital display either the air velocity or its standard deviation can be obtained. Both are displayed as an exponentially damped signal with a 6 seconds time constant and at the same time as a linear average for the last 3 minutes. Maximum displayed value is 1,00 m/s but peaks in velocity up to 1,50 m/s are accepted for both the damped and the averaged outputs.

The two damped signals, air velocity and its standard deviation, are also available as linearized analogue voltages on the rear panel along with the instantaneous air velocity, which normally fluctuates too fast to be read from a digital display. The latter is updated 20 times per second.

Air velocity data for certain preselected measuring periods, along with data from the other four transducers, may be stored in the memory of the 1213 for later read out on an X–Y recorder or on the display.

The different air velocity signals are calculated by the microprocessor in the following way: The instantaneous air velocity is sampled with a sampling interval of 0,4 s. The exponentially damped signal and its standard deviation are then determined using the recursion formulae:

$$v_n = v_{n-1} + \frac{v_s(n) - v_{n-1}}{16}$$

$$S_n = S_{n-1} + \frac{v_s^2(n) - S_{n-1}}{16}$$

$$< v >_{6\,\text{sec}} = v_n$$

$$\sigma_{6\,\text{sec}} = \sqrt{S_n - v_n^2}$$

Where: $v_s(n)$ = sample no. n of the instantaneous air velocity

$< v >$ = damped or mean air velocity

σ = standard deviation

The 3 minutes mean and its standard deviation are calculated every 10 s by storing the last 450 samples of the instantaneous air velocity and then applying the formulae:

$$V = \frac{1}{450} \sum_{n=1}^{450} v_s(n)$$

$$S = \frac{1}{450} \sum_{n=1}^{450} v_s^2(n)$$

$$< v >_{3\,\mathrm{min}} = V$$

$$\sigma_{3\,\mathrm{min}} = \sqrt{S - V^2}$$

Specifications for the Air Velocity Transducer Type MM 0038, in conjunction with the Indoor Climate Analyzer Type 1213.

Measurement range: 0,05 – 1,00 m/s (10 – 200 ft/min)
Operating temperature range: 5 – 40°C (41 – 104°F)
Response time: 0,2 s to 90% of step change.
Accuracy: ± 5% ± 0,05 m/s (10 ft/min) for flow from the front at any angle of incidence between – 165° and + 165° from the longitudinal axis.

These specifications comply with ISO 7726 for Moderate Thermal Environments, see B & K *Technical Review*, No. 1 – 1985.

Apparatus for Test and Calibration of the Air Velocity Transducer
For testing air velocity transducers during development and for calibration in production, it was necessary to develop a device which could produce uniform, steady air flow, whose velocity could be varied and known precisely. Furthermore, it should be possible to choose both the temperature and the angle of flow from the vertical. None of the existing types of equipment used for calibrating anemometers could meet all these demands, and this led to the invention of the Wind Wheel.

The operating principle of the Wind Wheel is based on the elementary fact, that when a closed container of any shape rotates with constant angular velocity, the air inside will follow it with precisely the same velocity, at least some time after the start of the rotation. The anemometer probe to be tested is inserted into the rotating mass of air through a

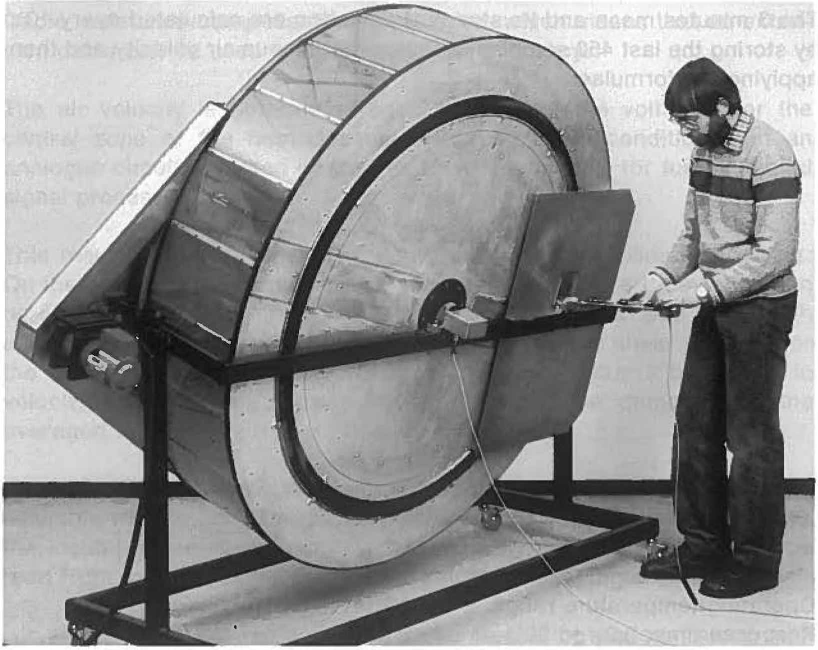

Fig. 3. The Wind Wheel

suitable slot. If the disturbance caused by the probe and the slot is sufficiently small, the air velocity around the probe will be equal to the velocity of the container at the same distance from the rotational axis.

The Wind Wheel is actually constructed as shown in Fig.3. The rotating container is disc-shaped with a diameter of 1,7 m and a thickness of 0,4 m. In one side there is a slot closed with two brush panels. The probe under test is placed in a hinged holder fitted with a "plough" to open the brushes.

The wheel is kept in constant rotational motion by a servo motor, and the resulting rotational speed, i.e. the air velocity can be monitored using the output from an angle encoder on the wheel axle. The wheel can produce air speeds from 0 to 10 m/s. The upper limit is set for safety reasons.

In order to ensure correct performance, any inside air flow relative to the walls of the wheel caused by the inserted probe must be negligible within less than one revolution. This is provided by vanes of damping material (metal nets) mounted inside the wheel perpendicular to the direction of movement. Each vane is provided with a cut-out to allow the probe to pass at a safe distance.

A specially designed ultra low velocity hot wire anemometer, developed to test the efficiency of the damping material, is mounted inside the wheel and rotates with it. This fast response anemometer has an excess temperature on the "hot" wire as low as 3°C, which makes it possible to detect air velocities lower than 1 cm/s. Even with this high sensitivity it is impossible to detect any movement relative to the wheel of the air impinging on the transducer under test, indicating that the wheel functions properly.

A patent is pending for the Wind Wheel.

The performance of the MM 0038 Air Velocity Transducer

The Wind Wheel is an invaluable tool, not only for calibration purposes, but also for investigating the overall performance of the MM 0038. The results of these investigations are discussed in the following section.

A number of possible sources of error inherent in thermal anemometers must be considered:

It is obvious that the output of the transducer is a function of the air velocity and the temperature difference between the air and heated surface. There are, however, a number of other factors involved, whose net effect in the ideal case should become negligible. In general, the heat transfer from the transducer will also depend on the following physical parameters:

1. The angle of incidence of the flow on the probe
2. The angle of the flow to the direction of gravity
3. Radiative heat exchange with the surroundings
4. Air temperature
5. Air pressure
6. Composition of the air

Directional sensitivity

There is more to constructing an omnidirectional thermal transducer than merely giving the heated surface a spherical shape. A spherical sensor needs some sort of rigid support, which unfortunately degrades the spherical symmetry. Initially the MM 0038 was designed as a **cylindrical** probe, resulting in an unacceptable directional sensitivity. The shape and length of the heated surfaces were then gradually changed until an optimum was reached. Unfortunately the present theoretical basis of the heat transfer mechanisms involved does not allow calculation of the optimal shape, so the optimization process had to be performed solely by experiment.

A special problem to be overcome is caused by the interaction of the two sensors. When the air strikes the probe head on, warm air from the upper sensor will cause a small temperature increase in the lower one, resulting in a significant increase of the output signal.

The probe is fitted with a solid sphere, whose size and distance from the upper sensor are chosen to reduce the air velocity just enough to compensate for the rise in output voltage. This approach has the advantage, that the solid sphere produces a more rugged probe tip than the foam ellipsoid.

The resulting directional sensitivity can be derived from Fig.4, which, for a number of air velocities, shows the unlinearized output from the MM 0038 as a function of the angle between flow and probe axis. The measurement was made in the Wind Wheel in a horizontal flow. The transducer was rotated slowly, at a constant angular velocity around a horizontal axis perpendicular to the transducer axis. This continuous measurement reveals details of the directional sensitivity, which would not have appeared in a point-by-point plot. The curves show that the optimization of the geometrical sensor parameters has resulted in a remarkably constant sensitivity, except for minor deviations in some directions.

Although the shaft has a streamlined shape, its "shelter effect" causes an unavoidable drop in sensitivity for $\theta = 180°$ for all velocities.

Other deviations occur at higher velocities; especially conspicuous is a narrow peak, which is observed for a direction almost transverse to the probe axis. This peak and other fine structure details of the sensitivity curves are highly reproducible for different transducers. Its exact nature is unknown, but it is probably caused by a shift in the flow pattern

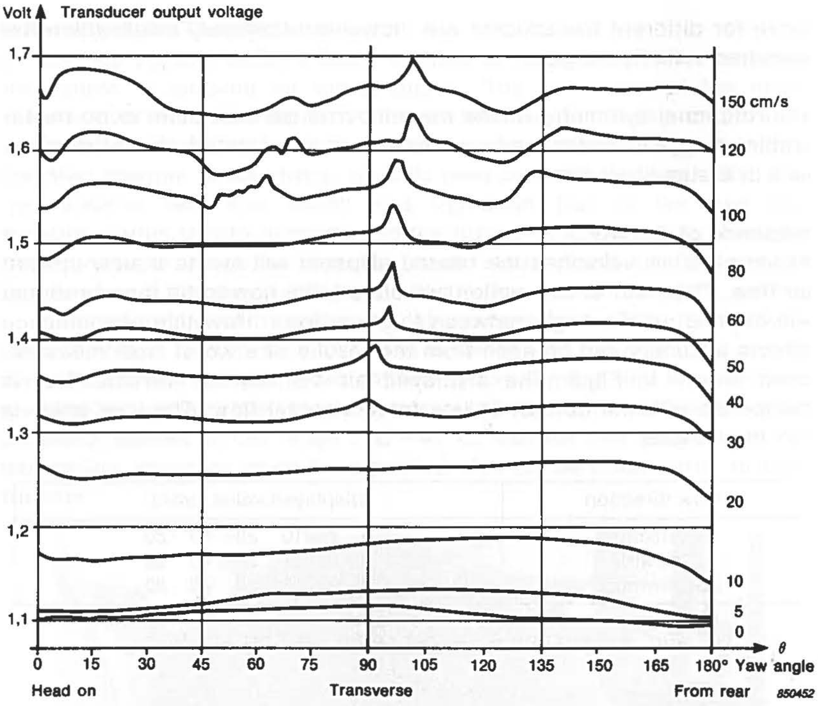

Fig. 4. Directional sensitivity. Rotation about an axis perpendicular to the probe's axis

around the ellipsoids. Due to the very narrow solid angle in which this phenomenon occurs, it can only be observed in a completely turbulence-free air flow, and will therefore not reduce accuracy of indoor air velocity measurements. It must, however, be emphasized, that the transducer should not be tested or recalibrated in an air flow in this particular direction.

Calibration during manufacture is performed in the Wind Wheel by making a fine adjustment of the sensor temperature difference. The velocity is 0,40 m/s, which is in the mid range of the specified velocity range and the yaw angle is 75°, which is on a flat part of the sensitivity curve.

Fig.4 also gives an idea of the nonlinearity of the calibration curve. The calibration curve stored in a PROM in the 1213 was determined as an average for a large number of transducers. The variations in calibration curve for different transducers are, however, extremely small within the specified velocity range.

The rotational symmetry of the transducer is perfect: there is no measurable change in transducer response when it is rotated about the probe axis in a steady air flow.

Influence of Gravity
At very low air velocities the heated ellipsoid will create a slow upward air flow. This natural convection will disturb the flow to be measured and will depend on the angle between the two flows. How this phenomenon affects accuracy can be seen from the results of a worst case measurement shown in Fig.5. The displayed air velocity for vertical flow is compared with the correct values for horizontal flow. The yaw angle is 75° in all cases.

Flow direction	Displayed value, cm/s					
Horizontal	5	7	10	20	40	80
Upwards	7	9	11	20	40	80
Downwards	0	3	8	19	40	80

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Fig. 5. Transducer response for vertical air flow

A lower probe temperature will reduce the deviations caused by natural convection, but it will increase the demands on the electronic circuit and on the long term stability of the probe resistors. A probe temperature difference of 13°C was chosen as a compromise between these contradictory demands.

Influence of Thermal Radiation
Due to the symmetrical construction of the MM0038 it is intrinsically insensitive to thermal radiation: Since the two ellipsoids are identical, the radiation will induce the same temperature shift in each. There may, however, be small differences between the two ellipsoids, originating from the manufacturing process. These may cause some sensitivity to thermal radiation. By way of example, an infrared radiation field with a radiant temperature 10°C higher or lower than the air temperature will cause a deviation in displayed air velocity of less than 0,01 m/s. In practice this error is negligible.

The white reflecting colour of the probe makes it insensitive to radiation in the visible and near-infrared region.

Influence of Air Temperature

At first sight it may seem difficult to make a thermal anemometer probe insensitive to ambient air temperature : The resistance of the nickel resistor over which the output voltage is measured is highly temperature dependent and so are the characteristics of the air, which govern heat transfer: thermal conductivity, specific heat capacity and viscosity. Also the radiative heat loss, which is a significant part of the total heat transfer, varies rapidly according to the Stefan-Boltzmann law. However, the transducer response can be made independent of the ambient temperature if the sensor temperature difference is not constant, but has a small decrease with increasing air temperature. This decrease is controlled by a fixed resistor inserted in series with the unheated sensor. The value of this resistor is determined by experiment, and is selected to give the transducers the same response at 10°C and 35°C. The specified accuracy applies to the range 5°C – 40°C. Outside this range a rapidly decreasing accuracy must be expected, due to the nonlinearity of heat transfer.

Fig. 6. An experiment with the Wind Wheel in a vacuum chamber for measuring the air pressure correction

Influence of Air Pressure

The heat transfer from the probe will also depend on the air density and consequently on barometric pressure. The daily variations in barometric pressure at sea level are of no importance, but if, for instance, the instrument is used on locations in the mountains or in aircraft a significant drop in air pressure should probably be taken into account.

The effect on the MM 0038 of varying air pressure has been measured using the Wind Wheel. The Danish lowland doesn't offer many opportunities to test the effect of changing altitudes on measurements, so an experiment was performed in a large vacuum chamber, shown in Fig.6.

The results of this experiment are listed in a correction table (Fig.7), which shows that at altitudes higher than approx. 1000 m above sea level

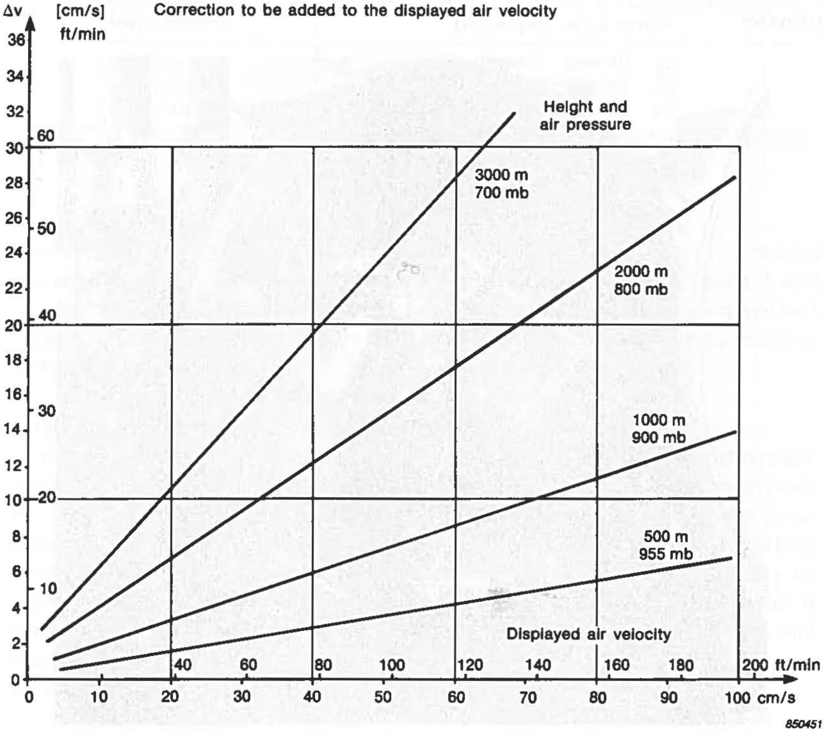

Fig. 7. Air pressure correction for the Air Velocity Transducer Type MM 0038

corrections must be applied to the measured value in order to obtain true values for the air velocity.

However, the displayed air velocity is actually a measure of the cooling effect of the draught. If the purpose of the measurement is to determine this, the displayed value should not be corrected, even at high altitudes.

Influence of Humidity

It is reasonable to assume that the (physical) characteristics of atmospheric air depend on its composition. The only constituent of atmospheric air, whose amount can vary significantly is water vapour. The change in output from the MM 0038 was measured as a function of a change in water vapour pressure. At an air velocity of 1 m/s it was found that there will be a decrease of 1 cm/s for an increase in water vapour pressure of 1 kPa. This change of response is of no practical importance. However, to obtain the highest possible accuracy, humidity and pressure corrections are made when the transducers are calibrated, so they will measure correctly at a water vapour pressure of 1,2 kPa and an air pressure of 1013 mb. At 20°C this water vapour pressure is the equivalent of a relative humidity of 50%.

The Step Response of the MM 0038

The ability of the MM 0038 to detect rapid variations in air velocity has been determined by measuring how the transducer responds to a sudden change in air velocity. The experiment was performed with the transducer traversing inside a closed box with still air, driven by a servo motor. As an example, Fig.8 shows the output from the Indoor Climate Analyzer during a sudden acceleration of the transducer from 8 cm/s to 42 cm/s. It can be seen that the time to reach 90% of the step change is approximately 0,2 s.

The step response time is actually somewhat shorter, due to the finite acceleration in this experiment. The stepwise change in output voltage is caused by the digitizing of the signal, and the noise is caused by small fluctuations in transducer velocity.

When a step change in air velocity is measured, all hot film probes tend to reach the final output voltage very slowly. This phenomenon is caused by temperature changes in the substrate. In the MM 0038 this is minimized by using a substrate with a very low thermal conductivity and heat capacity.

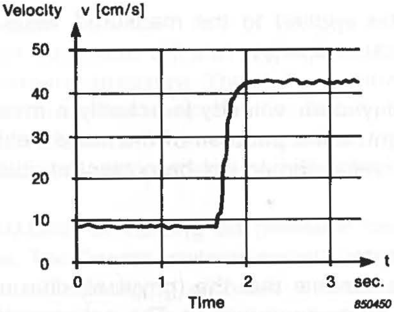

Fig. 8. A step response curve for the MM 0038

Handling of the Velocity Probe

Due to its special design, the MM 0038 is far more resistant to mechanical hazards than current thermal anemometers. It should nevertheless be handled as a precision instrument. This means in practice, that it may be damaged if it is accidentally dropped on the floor or if the ellipsoids are struck by sharp objects.

Concluding remarks on Accuracy

The investigations of error sources described above show that the main contribution to the measuring error of the MM 0038 is caused by the directional sensitivity and to some extent by the natural convection. All other sources of error are of minor importance. A better accuracy than specified can be obtained if the direction of the air flow can be determined, e.g. by observing smoke. However, in practice this is not very useful: One reason is, that the direction of the air velocity generally varies appreciably during the time needed to obtain an accurate evaluation of the air velocity. The other reason is, that the specified accuracy is quite sufficient for indoor climate investigations.

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